Just-in-time Compilation (JIT)

Seminar: Automation, Compilers, and Code-Generation
Chair: High Performance and Automatic Computing
RWTH AACHEN UNIVERSITY

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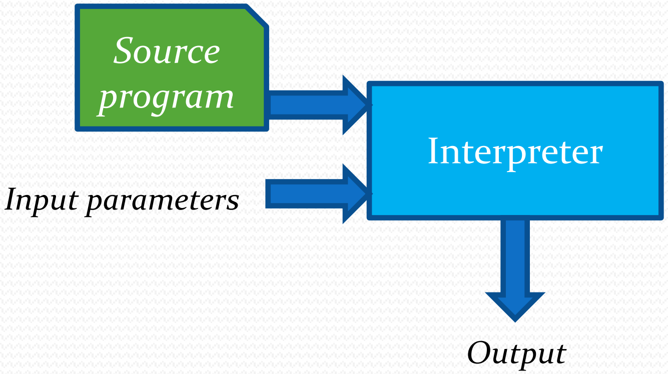
Outline

- **Overview**
  - **Static Compilation**
  - **Virtual machines**
  - **Traditional Approaches**
- JIT
  - Defining JIT
  - JIT: A Combination of two traditional approaches
- Working Mechanism
  - Conceptual Idea
  - Technical steps
  - Advantages & Drawbacks
- Applications
- Exploring JIT & java
  - Compilation in java
  - VM & JVM
  - JIT in JVM
  - Runtime optimizations by JIT
- Startup Delay and Possible Optimizations
  - Java HotSpot

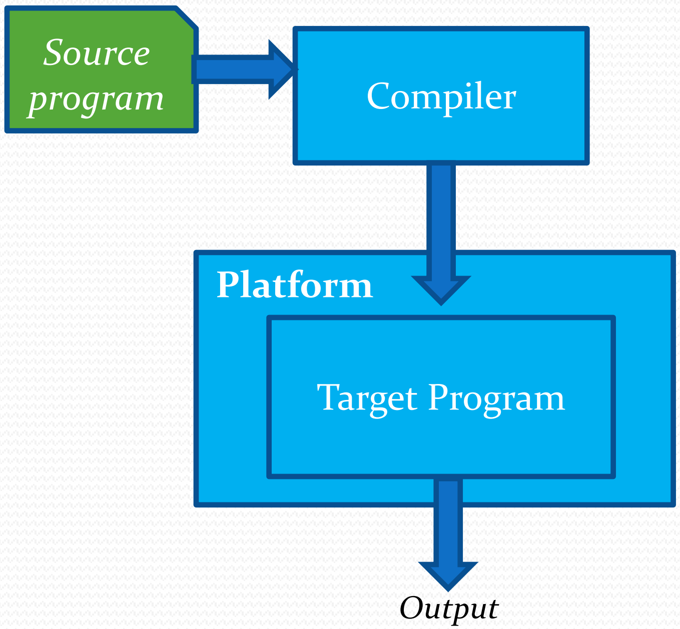
Compiler and Interpreter

Basic conceptual view of both techniques, remember they are not mutually exclusive.



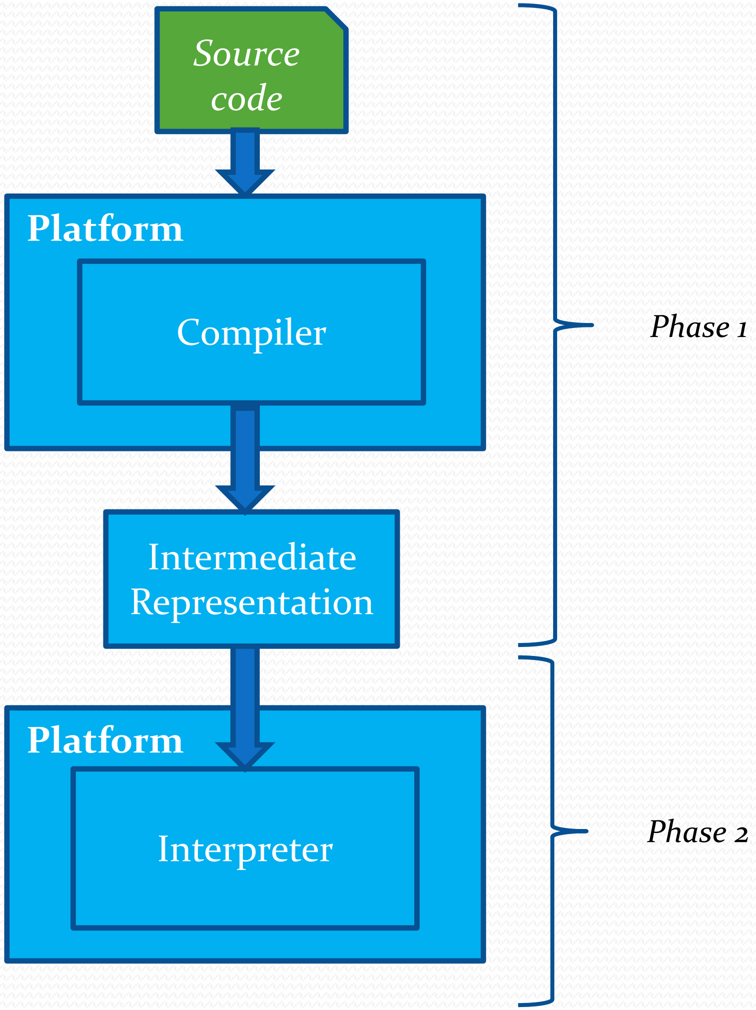
- Performs actions described by high level program.
- Generate machine code and then walk a parse tree for execution

  OR
- Generate and execute intermediate software-defined instructions.
- Perform some conversion work every time a statement or function is executed



- Produce machine code directly executable by computer hardware.
- Generates a stand-alone machine code program.
- Can make almost all conversions from source to the machine level at once.

Hybrid Compilation/Interpretation



Which one is better ?

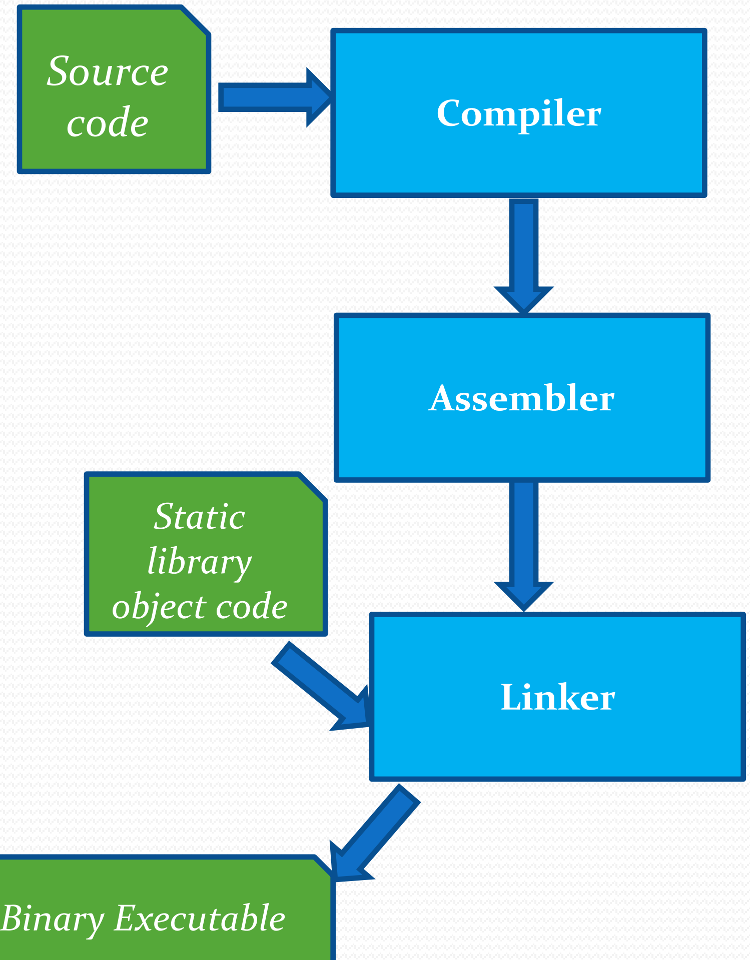
- *Compilation*
- *Interpretation*
- *Hybrid*

Static Compilation

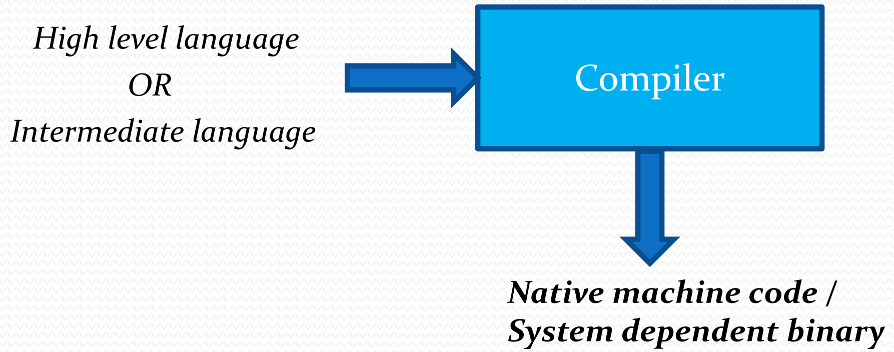
- Translate from high level language to machine code.
- All bindings are done at compile time.
- Linking is done during the creation of an executable.
- Linker resolves the referenced symbols.

Robust, better security, before hand optimization, reduced start-up cost

Compatibility concerns, Less opportunity for performance improvement, dynamic traits exploitation, infeasible speculative optimization



Ahead of Time Compilation (AOT)



"Performs compilation before execution rather than during execution."

- Trade offs:
  - Memory
  - Starting time
  - Portability
  - Optimizations

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Defining JIT

"**Just-In-Time (JIT) compilation**, also known as **dynamic translation**, is compilation done during execution of a program at run time rather than prior to execution" [*]

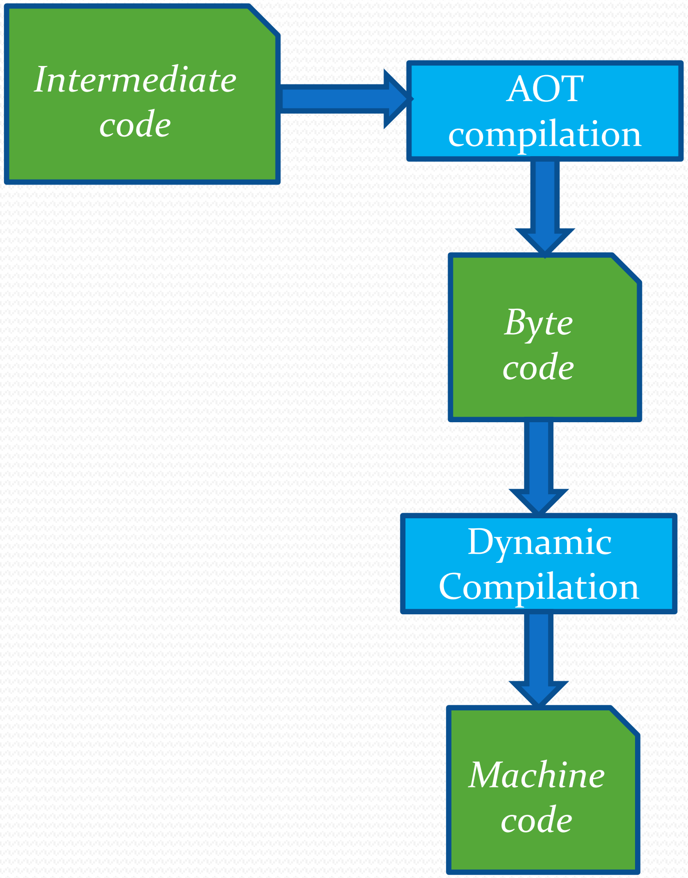
JIT: A combination of approaches

- JIT compiler represents a hybrid approach.
- “Speed of compiled code” and “Flexibility of Interpretation”
- Combining two approaches brings pros and cons of both techniques.

- Selectively compile the most frequently executing methods to native code during execution.

Cont.

- Conceptual view of JIT



- Translate continuously.
- Perform caching of compiled code.
- Minimizes lag on future execution of same code during a given run.

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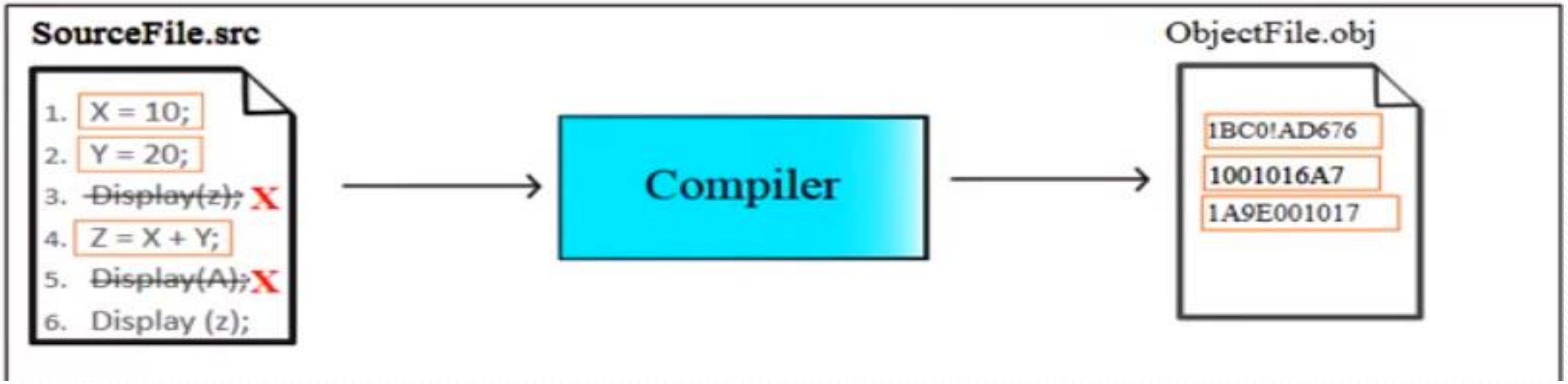
Conceptual Idea

- Compiler

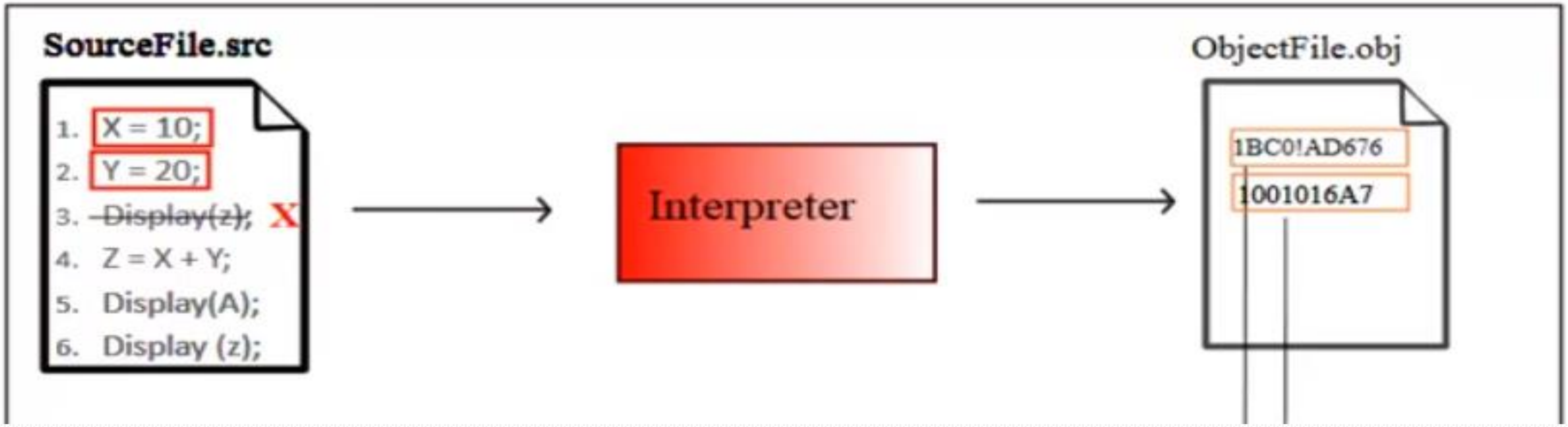
[*]



Cont..

- Interpreter

[*]



Cont.

- JIT

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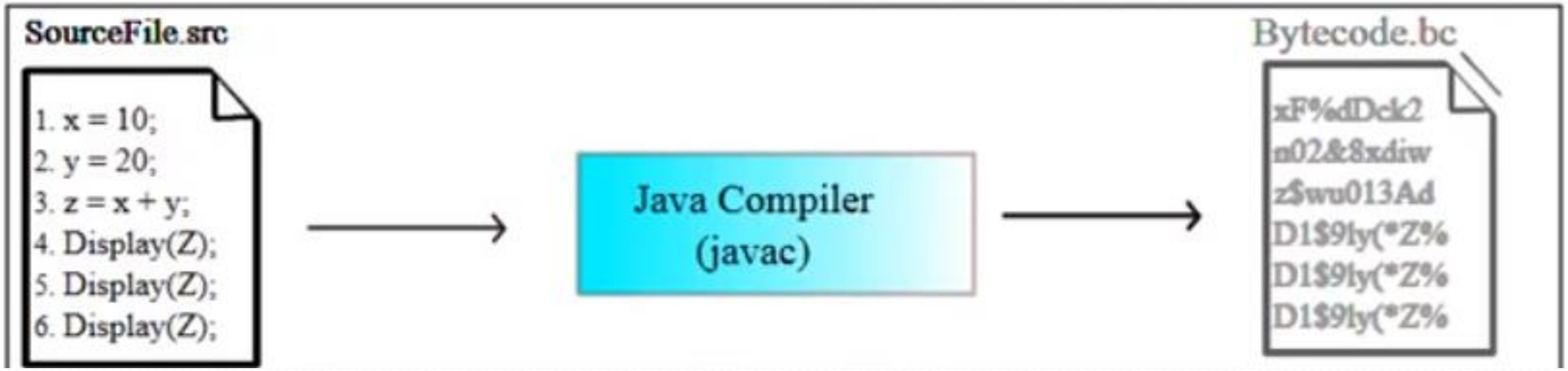
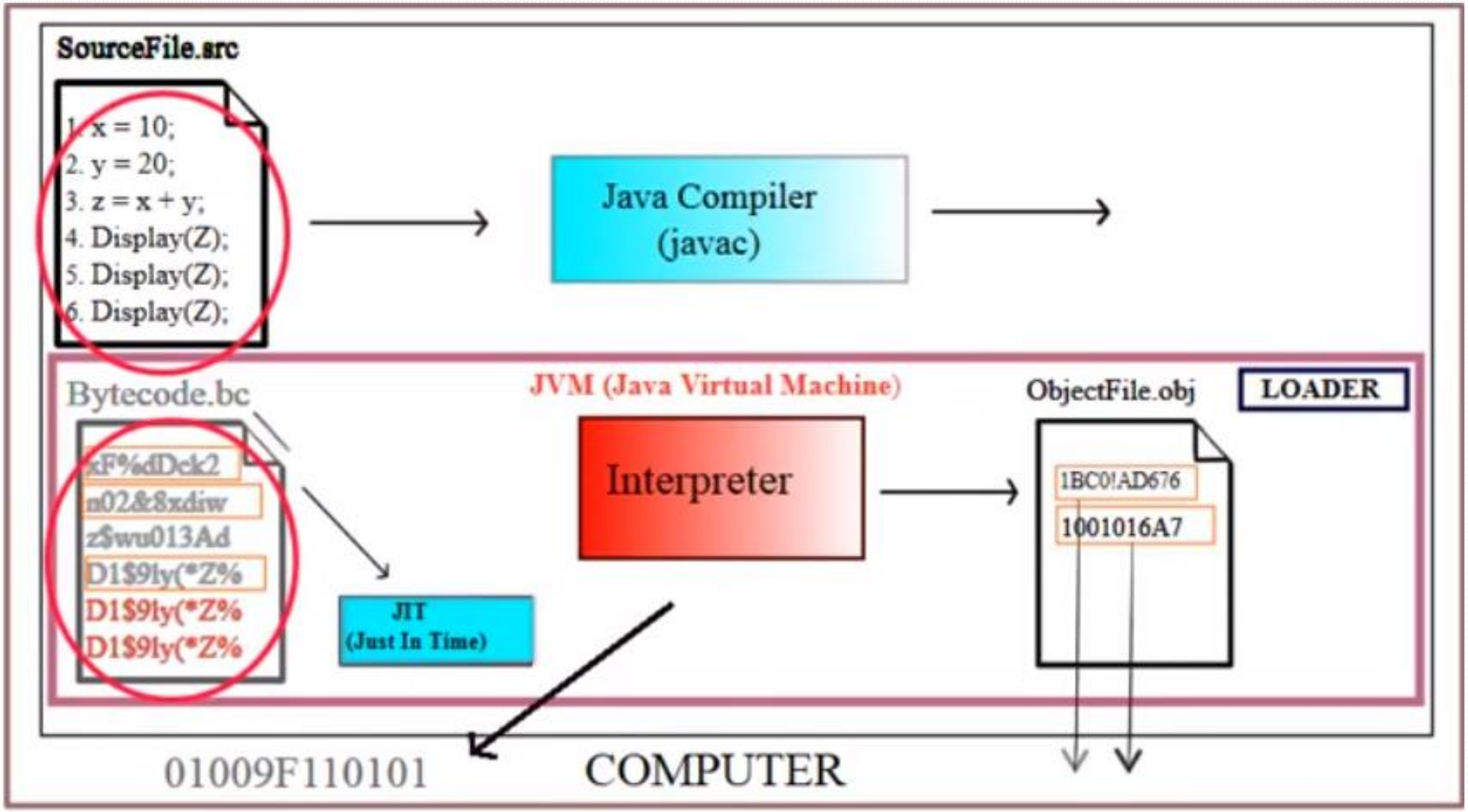

SourceFile.src
1. x = 10;
2. y = 20;
3. z = x + y;
4. Display(Z);
5. Display(Z);
6. Display(Z);
Java Compiler
(javac)
Bytecode.bc
xF%dDck2
n02&8xdiw
z$wu013Ad
D1$9ly(*Z%
D1$9ly(*Z%
D1$9ly(*Z%

Cont.

- JIT

[*]



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Java Compiler
(javac)
Bytecode.bc
JVM (Java Virtual Machine)
ObjectFile.obj
LOADER
xF%dDck2
n02&8xdiw
z$wu013Ad
D1$9ly(*Z%
D1$9ly(*Z%
D1$9ly(*Z%
Interpreter
1BC0!AD676
1001016A7
JIT
(Just In Time)
01009F110101
COMPUTER

Technical Steps

- We can divide JIT into distinct phases mainly:
  - Machine code creation at runtime .
  - Machine code execution at runtime.

- Machine code creation

$$\underbrace{\textit{Intermediate code} \Rightarrow \textit{Machine code}}_{\textit{at runtime}}$$

  - This step is similar to what every compiler does with slight difference.
  - Create machine code at program run time.
  - Use building blocks for keeping code in memory for execution later.
  - Easier to write

- Machine code execution (involved roughly three main steps):
  - Allocate a readable, writable and executable chunk of memory on the heap.
  - Copy the machine code implementing intermediate code into this chunk.
  - Execute code from this chunk by casting it to a function pointer and calling through it.
- Example: (for details, please visit link)

```
// Allocates RWX memory of given size and returns a pointer to it. On failure,
// prints out the error and returns NULL.
void* alloc_executable_memory(size_t size) {
  void* ptr = mmap(0, size,
                   PROT_READ | PROT_WRITE | PROT_EXEC,
                   MAP_PRIVATE | MAP_ANONYMOUS, -1, 0);
  if (ptr == (void*)-1) {
    perror("mmap");
    return NULL;
  }
  return ptr;
}
```

2

```
long add4(long num) {
  return num + 4;
}
```

1

```
void emit_code_into_memory(unsigned char* m) {
  unsigned char code[] = {
    0x48, 0x89, 0xf8,                   // mov %rdi, %rax
    0x48, 0x83, 0xc0, 0x04,             // add $4, %rax
    0xc3                                // ret
  };
  memcpy(m, code, sizeof(code));
}
```

3

```
const size_t SIZE = 1024;
typedef long (*JittedFunc)(long);

// Allocates RWX memory directly.
void run_from_rwx() {
  void* m = alloc_executable_memory(SIZE);
  emit_code_into_memory(m);

  JittedFunc func = m;
  int result = func(2);
  printf("result = %d\n", result);
}
```

4

Advantages and Drawbacks

- Faster execution.
- Easier handling of late bound data types.
- Enforce security guarantees.
- Can be optimized to targeted CPU and operating system
- Portable byte code.
- Can use profile information to perform optimizations.
- Can perform other many different runtime optimizations.

- Startup delay.
- Limited AOT optimizations because of time.
- Compiler should be packaged inside virtual machine.
- Can not perform complex optimizations which are possible with static compilation.
- Maintenance and debugging can be a headache.
- Security concerns

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Applications

Many different companies/organizations have adopted JIT in there tools, some of renown are:

- Oracle Java
  - The Just-In-Time (JIT) compiler is a component of the Java™ Runtime Environment that improves the performance of Java applications at run time.
- Microsoft .NET Framework
  - The JIT compiler is part of the Common Language Runtime (CLR). The CLR manages the execution of all .NET applications.
- JIT in web browsers
  - Trace Monkey is a trace based JIT compiler used by Mozilla Firefox browser to run JavaScript programs
- LLVM
  - intro

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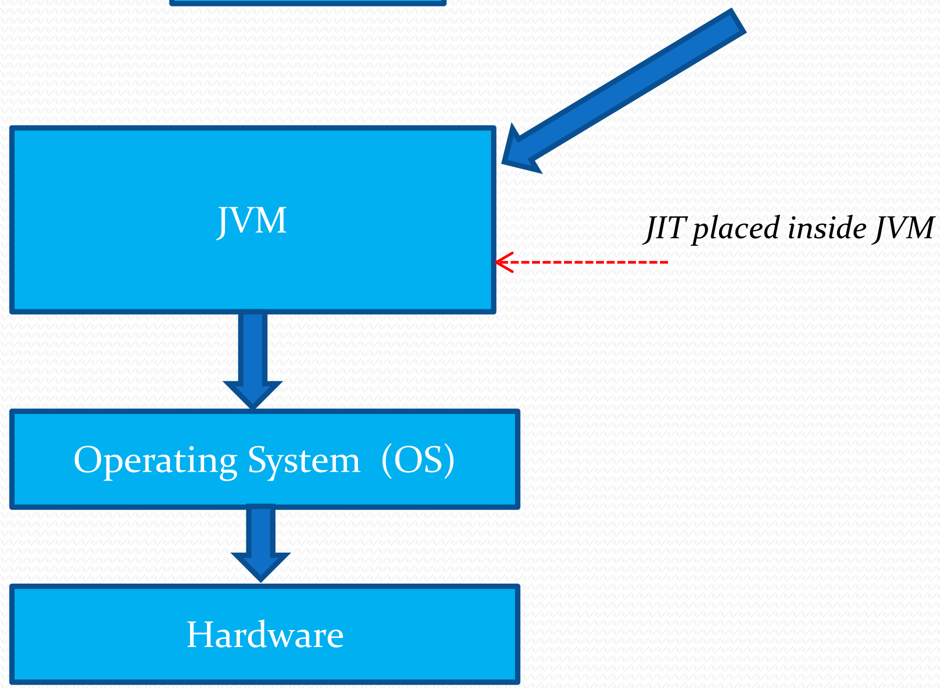
Compilation in java

Conceptual view of code compilation in java.

- Java source code is compiled by java compiler resulting in JVM readable java byte code.
- JVM performs following two main steps:
    - Compiles byte code at runtime into
    - machine readable instructions
- Execute compiled machine readable code



Virtual Machine

- Different kind of virtual machines provide different functions.

- Some of the important goals of VM to consider:
  - Portability.
  - Bridge the gap between compilers and interpreters.

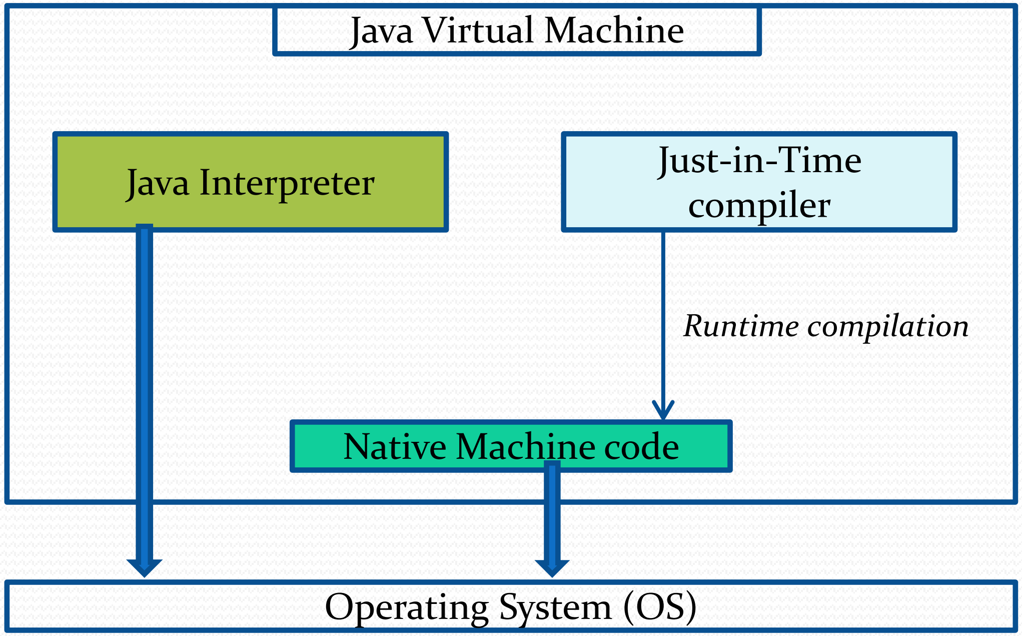
- A virtual machine need at least following three basic components:
  - Interpreter
  - Runtime Supporting System
  - Collection of libraries

- Some of the major concerns:

  - Efficiency
  - Multiple VM's concurrency issue.
  - Compatibility with host for malware protection.

JVM

- JVM comprises following main features:
  - Runtime
    - Mainly handles class loading , byte code verification and other required functions.
  - JIT
    - Profiling, compilation plans, optimizations
  - Garbage Collection



JIT in JVM

Improves the performance of Java programs by compiling byte code into native machine code at run time.

- JIT compiler is by default enabled , however it gets activated when a Java method is called.
- Performs on runtime: *Method code* → *Machine code*

  JVM having the machine code does need to interpret it, results in improving processor time and memory usage

- JIT compilation threshold helps to take action.
- JIT recompilation threshold helps to make optimization decisions.

JIT'ing requires Profiling

- Collect data during execution:
  - Executed functions
  - Executed paths
  - Branches
  - Parameter values
- Collecting data at right time:
  - Early or late phase
  - Continue or intermittent way
- Collecting data by:
  - Sampling
  - Program instrumentation
  - Using hardware performance measures
- Use collected data for:
  - Optimizations

Runtime Optimizations by JIT

- During the compilation performed by JIT, it performs following main optimization steps:
  - Inlining
  - Local optimizations
  - Control flow optimizations
  - Global optimizations
  - Native code generation

Inlining

"Replaces a function call site with the body of the called function"[*]

- Trees of smaller methods are "inlined", into the trees of their callers.

[*]

Before

```
int addAll(int max) {
    int accum = 0;
    for (int i = 0; i < max; i++) {
        accum = add(accum, i);
    }
    return accum;
}

int add(int a, int b) { return a + b; }
```

[*]

After

```
int addAll(int max) {
    int accum = 0;
    for (int i = 0; i < max; i++) {
        accum = accum + i;
    }
    return accum;
}
```

Cont..

Optimizations performed in this phase are:

- Trivial Inlining
  - Inlining short, simple functions can save both time and space
- Call graph inlining
  - Create a call graph and evaluate important parts by traversing.
- Tail recursion elimination
  - Similar to tail-call elimination with added constraint i.e. calling itself.
- Virtual call guard optimizations
  - Perform by devirtualization

What about ?

Local Optimizations

"Improve small portion of code at a time"

Mainly includes:

- Local data flow analyses and optimizations
  - Information collection about the data flow values across basic blocks.
  - Compute data flow equations and optimize such as:
    - Ambiguous or duplicate definitions
    - Remove redundant expressions
- Register usage optimization
- Simplifications of Java™ idioms
  - VarargsCollectionFactoryMethod

Control flow optimizations

"Analyze the flow of control inside a code section and rearrange code paths to improve the efficiency."

Mainly includes:

- Code reordering
- Loop optimizations
  - Inversion
  - Reduction
  - Versioning and specialization
- Switch analysis
- Dead code elimination

Global optimizations

"Perform optimizations on entire method at once"

Mainly includes:

- Global data flow analyses and optimizations
- Optimizing garbage collection and memory allocation
- Partial redundancy elimination
- Optimizing synchronizations

Native Code Generation

Performing optimization during native code generation depends upon the underlying architecture, generally it performs:

- Translation of method trees into machine code.
- Perform minor optimizations as required.

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Startup Delay by JIT

- Time taken by JIT to load and compile the byte code cause delay in preliminary execution. This initial delay is known as “startup delay”
- For having better generated code, JIT performs more optimizations which also increase startup delay.

$$\textit{Increased Optimizations} \propto \textit{Better Code Generation}$$

$$\textit{Increased Optimizations} \propto \textit{Startup delay}$$

- Increased startup delay can also be because of IO-bound operations

HotSpot

"Combines interpretation, profiling, and dynamic compilation"

- Initially it runs as an interpreter and only compiles the "hot" code

Most frequently executed code

- Performs profiling to identify frequently execute code sections.
- Time is saved by not compiling the infrequent code.
- Profiling data help to improve decision making for optimizations.
- Apply adaptive optimization technology, includes:
  - HotSpot Detection
  - Method Inlining
  - Dynamic Deoptimization

Cont..

HotSpot comes with two compilers:

- The client compiler
  - Reduce application startup time.
  - Reduce memory footprint.
  - Less time for compilation
- The server compiler
  - Intended for long-running server applications.
  - Maximize peak operating speed.
  - Apply complex optimizations.

HotSpot Optimizations

HotSpot include number of complex and advanced optimizations, some of them are mentioned below:

- Deep inlining:
  - Method inlining combined with global analysis and dynamic deoptimization
- Fast instanceof/checkcast
  - Accelerating the dynamic type tests
- Range check elimination:
  - Surety about the index bound to remove index bound check.
- Loop unrolling:
  - Enables faster loop execution
- Feedback-directed optimizations:

References

- https://en.wikipedia.org/wiki/Static_build
- http://slideplayer.com/slide/6971785/
- https://en.wikipedia.org/wiki/Interpreter_(computing)
- http://programmers.stackexchange.com/questions/246094/understanding-the-differences-traditional-interpreter-jit-compiler-jit-interp
- http://slideplayer.com/slide/5821419/
- https://en.wikipedia.org/wiki/Ahead-of-time_compilation
- http://programmers.stackexchange.com/questions/246094/understanding-the-differences-traditional-interpreter-jit-compiler-jit-interp
- https://en.wikipedia.org/wiki/Just-in-time_compilation
- https://www.ibm.com/support/knowledgecenter/SSYKE2_7.0.0/com.ibm.java.zos.70.doc/diag/understanding/jit_overview.html
- http://www.slideshare.net/ZeroTurnaround/vladimir-ivanovjvmjitcompilationoverview-24613146
- https://www.safaribooksonline.com/library/view/java-performance-the/9781449363512/ch04.html
- https://en.wikibooks.org/wiki/Introduction_to_Programming_Languages/Interpreted_Programs#Just-in-Time_Compilation
- http://eli.thegreenplace.net/2013/11/05/how-to-jit-an-introduction
- https://www.youtube.com/watch?v=8yoL9QT7U74
- http://www.oracle.com/technetwork/java/whitepaper-135217.html#scalability

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Thanks for your precious time ☺

Any Questions ?